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Uses of Ground-Penetrating Radar in the Georgia Coastal Plain

Review of Past and Current Studies

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Abstract

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Soils in the Coastal Plain region of Georgia vary in depth, texture, depth to water table, and various other chemical, physical, and morphological properties. Nondestructive and cost-efficient ways are needed to determine lateral extent and depth of soil diagnostic features that cause lateral and preferential flow of water and agrichemicals. Ground-penetrating radar (GPR) has been used by researchers at ARS's Southeast Watershed Research Laboratory (SEWRL) to nondestructively investigate soil properties (and their spatial variability) and geologic materials in this region. The GPR used was a Subsurface Interface Radar (SIR) System-8 impulse radar. Four antennas with center frequencies of 80, 120, 300, and 500 MHz have been used. This GPR provides nondestructive, continuous images of subsurface interfaces. Limitations and past and current uses of GPR at SEWRL are summarized. Uses of GPR include mapping soils and performing nondestructive site investigations; detecting and determining spatial variability of argillic horizons, water tables in coarse-textured soils, geologic materials, and hard pans; and mapping lake bottoms and defining lake storage conditions.

Keywords: ground-penetrating radar, water tables, preferential flow, soil horizons

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Contents

Figures

Uses of Ground-Penetrating Radar in the Georgia Coastal Plain
Review of Past and Current Studies

C.C. Truman, D.D. Bosch, H.D. Allison, and R.G. Fletcher

Soils developing in the Coastal Plain region of Georgia vary in depth, texture, depth to water table, and various other chemical, physical, and morphological properties. Many of these soil subsurface features and properties influence water and agrichemical (nutrients and pesticides) movement through these soils. Nondestructive and efficient methods are needed to determine lateral extent and depth of diagnostic features found in these soils. Traditional methods of determining soil properties and features involve extensive sampling—a time-consuming, laborious process that provides limited (point) data that are difficult to relate to surrounding areas or between sampling points. Ground-penetrating radar (GPR) is a research tool that can quickly and accurately provide continuous, nondestructive profiles on depth to and lateral extent of selected soil features and provide data on soil features between observation points.

Radar was first used in World War II to detect airplanes. Since then, radar has been used to measure soil water, soil surface roughness, and vegetative cover. In the 1960's the military adapted radar technology to track vehicles, to measure the thickness of concrete and asphalt, and to locate soil voids and buried objects. In 1979 the feasibility of using GPR for soil investigations was successfully demonstrated in a study conducted by NASA, the U.S. Department of Agriculture's Soil Conservation Service, and the Florida Department of Transportation (Benson and Glaccum 1979, Johnson et al. 1979). Since then, GPR units have been used in many areas of the United States (45 of 50 states) for many different applications.

Researchers at the Southeast Watershed Research Laboratory (SEWRL) in Tifton, GA, purchased a GPR unit in 1983 and have done much work with GPR since that time. The purpose of this paper is to present past and current applications of GPR in the Coastal Plain region of Georgia and discuss problem areas and limitations in GPR research being conducted at SEWRL.

Truman is a soil scientist, Bosch is a hydraulic engineer, and Allison and Fletcher are GPR technicians, U.S. Department of Agriculture, Agricultural Research Service, Southeast Watershed Research Laboratory, P.O. Box 946, Tifton, GA 31793.

GPR System

The GPR unit used in all studies at SEWRL is the Geophysical Survey Systems, Inc., Subsurface Interface Radar (SIR) System-8 impulse radar. This unit is a broadband, video-pulse radar that provides a nondestructive, continuous profile of subsurface features. The time-scaled system measures the time a shortwave electromagnetic pulse takes to travel from the antenna to a detectable subsurface interface and be reflected back to the antenna. Velocity at which an electromagnetic pulse travels through a material is a function of the effective conductivity and relative dielectric constant of the material. Signal quality depends on changes in dielectric constant (K_a).

Four antennas, with center frequencies of 80, 120, 300, and 500 MHz, were used in various GPR studies. For deep-probing investigations, the 80-MHz antenna was used; for near-surface investigations, the 500-MHz antenna was used. However, the 120-MHz antenna was used for most studies and applications.

The GPR unit is mounted on a small trailer and towed by a small 18-hp tractor at speeds of 0.5–1.0 km/hr (0.3–0.6 mi/hr). When the unit is used to map reservoirs and lakes, it is mounted in a boat and the antenna is towed behind the boat in a plywood box at the same speeds mentioned above. Power requirement for the radar system is about 360 watts and is supplied by three 12-volt, automotive-type batteries connected to a 600-watt generator and battery charger to keep voltage constant.

Past Applications of GPR at SEWRL

Previous studies conducted by SEWRL researchers have involved a wide range of GPR uses. Objectives of these studies were as follows: (1) to determine the ability of GPR to penetrate selected soil features in the Coastal Plain region of Georgia, (2) to evaluate GPR as a tool for detecting depth to and lateral extent of diagnostic subsurface features in Coastal Plain soils, and (3) to determine factors that affect GPR's performance in Coastal Plain soils. The first objective has been documented (Asmussen et al. 1986, Truman 1986). The information that follows concentrates on objectives 2 and 3.

Determining Spatial Variability of Argillic Horizons

GPR has been used to determine spatial variability of argillic horizons in many Coastal Plain soils (Asmussen et al. 1986; Truman et al. 1988a,b; Hubbard et al. 1990). Argillic horizons generally have increased clay content, bulk density, water-holding capacity, and K_a than horizons above the argillic horizon (table 1). Abrupt changes in K_a produce strong reflections and distinct GPR images (fig. 1).

Asmussen et al. (1986) used GPR as a method to map soil variability within soil units. They used GPR to delineate five soils (Tifton loamy sand, Fuquay sand, Bonifay sand, Lakeland sand, and Kershaw sand), all of which have argillic horizons except Kershaw sand. Ground-truth was determined at predetermined sites (12-m grid) to obtain soil morphological descriptions. A positive linear relationship was found between measured depth to the argillic horizon and GPR-determined depth to the argillic horizon (fig. 2) (Asmussen et al. 1986, Truman et al. 1988b).

Truman et al. (1988b) used GPR to detect and determine the spatial variability of argillic horizons in eight soils (Albany sand, Dothan loamy sand, Fuquay sand, Kershaw sand, Ocilla loamy sand, Pelham loamy sand, Tifton loamy sand, and Troup sand). Representative sites of each soil series were selected, and pits were dug to prepare soil descriptions. Horizontal holes were bored in the side of all pits just above the argillic horizon, and a metal pipe was inserted into each hole. GPR images of pits containing the pipes were obtained. Transects (30-m intervals) were laid out on three areas of the Coastal Plain of Georgia. Each transect was a toposequence containing at least four or more soils mentioned above.

Figure 1 shows radar images for a Fuquay sand at two machine settings. A pipe was placed horizontally at a depth of 100 cm. GPR was used to identify and scan the argillic horizon. GPR can detect embedded objects (soil augers, irrigation pipe, tree roots, etc.). These features give a "Christmas tree" appearance that is due to reflections of radar impulses. The argillic horizon for the Fuquay sand was described at 104 cm. Embedded pipes placed horizontally in soil pits served as depth calibrators and provided a reference point to the argillic horizon. Spatial variability of depths to the argillic horizon was determined with GPR (fig. 3). Tic-marks (30-m intervals) represent points where ground-truth data were collected. Depth to the argillic horizon can be determined at any given point along this transect using ground-truth data and GPR imagery.

Mapping Soils

Use of GPR with traditional methods of soil sampling would reduce the time and cost of conducting soil surveys and increase the accuracy of soil surveys. Researchers at SEWRL have used GPR to determine the presence, depth, and lateral extent of soil horizons, and therefore, classify soils and distinguish among soil mapping units (Asmussen et al. 1986, Truman et al. 1988a, Hubbard et al. 1990). Soils in the southeastern United States are highly weathered and are classified based on the presence or absence of subsurface horizons. For example, many Coastal Plain soils are classified based on depth to the argillic horizon.

Asmussen et al. (1986) used GPR to delineate soil series (Lakeland sand, Bonifay sand, Fuquay sand, and Tifton loamy sand) within soil mapping units (fig. 4). They concluded that GPR could graphically display variation in depth to argillic horizons for different soil series along a transect and that GPR was more accurate when depth to the argillic horizon was relatively deep (greater than 50 cm).

Truman et al. (1988a) used GPR to produce subsurface images of 12 soil series in the Coastal Plain region of Georgia. Representative mapping units were defined by preliminary borings. Soil morphological descriptions of each pedon were made from soil pits and samples taken from each genetic horizon. Pipes were inserted into horizontal holes just above the argillic horizon of each soil.

Determining Spatial Variability of Water Tables, Geologic Materials, and Wetting Fronts

Information about depth to water tables, fluctuations of the water table, and soil water movement to the water table is needed to characterize the hydrologic cycle and chemical transport in a given area. GPR has been used to detect and determine spatial variability of the water table and water fronts in soil (Truman et al. 1988b, Smith et al. 1989, Vellidis et al. 1989).

Table 1. Physical properties of Coastal Plain soils at selected depths

Soil series	Depth* (cm)	Clay (%)	Bulk density (g/cm³)	Water-holding capacity 1/3 (bar)	Water-holding capacity 15 (bar)	Field† Θ (%)	Field† K_a
Alapaha	36–66	1.9	1.54	3.7	1.3	5.7	4.0
	94–109	16.1	1.91	12.2	7.7	23.3	12.2
Albany	0–13	3.6	--	7.2	4.4	--	--
	114–140	10.1	--	17.8	8.9	--	--
Carnegie	0–28	7.0	1.63	9.7	3.7	15.8	7.9
	28–50	37.6	1.73	15.0	10.2	25.9	13.9
Clarendon	0–25	4.5	1.56	7.0	2.7	13.1	6.6
	25–48	14.2	1.68	10.3	4.8	21.2	10.8
Dothan	0–20	3.5	1.42	4.6	2.2	3.3	3.5
	51–69	25.5	1.70	13.7	9.9	25.3	13.5
Fuquay	0–23	3.1	1.39	3.5	1.8	4.9	3.8
	104–125	23.2	1.72	11.8	9.9	25.9	13.9
Leefield	0–25	3.5	1.61	5.5	2.1	8.9	4.9
	74–104	13.6	1.77	8.8	4.8	25.6	13.7
Ocilla	0–18	3.0	1.51	4.9	2.4	9.4	5.1
	86–107	14.0	1.67	7.8	5.9	24.3	12.8
Pelham	0–28	2.4	1.48	4.9	2.8	9.0	5.0
	114–150	12.4	1.64	11.4	9.1	28.2	15.6
Tifton	0–20	5.4	1.61	7.0	2.8	4.9	3.8
	36–90	36.4	1.78	19.7	12.7	23.2	12.1
Troup	64–89	3.7	1.54	5.1	1.5	23.6	12.3
	114–145	14.2	1.70	10.9	5.6	29.3	16.4

* The deeper depth for each soil represents the argillic horizon.

† Θ, Volumetric water content. K_a, dielectric constant.

Source: Truman et al. (1988a).

Truman et al. (1988b) used GPR to determine water table positions in a Kershaw sand (fig. 5). The Kershaw series includes relatively coarse-textured sands that generally have a distinct water table and abrupt boundary between deposited overburden and geologic material. Tic-marks (30 m apart) represent positions of wells that were placed along the transect. Data from these wells provided information on depth to the water table and geologic material. Depth to the water table and geologic material at any point along the transect can be determined by GPR imagery. A linear relationship was found between measured depth to the water table and depth determined by GPR (fig. 6) (Truman et al. 1988b, Smith et al. 1989). Radar images of water tables appear as the inverse of the topography in a given area. Regardless of elevation, the ground surface of all GPR images is always level. To alleviate this problem, we plotted relative elevations of the ground surface against horizontal distance (fig. 7). This plot reveals actual topography of the soil surface and shows the water table and clay contact (or geologic material) relative to the surface.

Smith et al. (1989) used GPR as a tool for locating the water table and underlying geologic material on a Lakeland sand. Profile depth for the Lakeland sand was restricted by the top of the Hawthorne formation and ranged in depth from 1.9 to 4.4 m. The surface soil had relatively uniform slope (4 percent), whereas the top of the Hawthorne material had slopes that ranged from 1 to 15 percent. Pipes were buried at selected depths for calibrating GPR, and seven transects were laid out. The 120-MHz antenna was used at a scanning time of 100 nanoseconds. GPR was used to map the position of the water table during a 10-day period (fig. 8). GPR-determined water table depths were compared with water table depths recorded in 28 wells located adjacent to the transects. Smith et al. (1989) concluded that GPR was a useful tool for monitoring locations of water tables in sandy soils and that only a few monitoring wells are needed in order to obtain a reliable depth calibration.

Vellidis et al. (1989) conducted a companion study to Smith et al. (1989) and used GPR as a tool for detecting soil water movement in relation to surface water application (uniformity). Soil, geologic materials, antenna, and scanning speed were the same as those used by Smith et al. (1989). Irrigation sprinkler risers were located on a 12- by 12-m grid throughout the field. The water application rate was 12.5 mm/hr. A total of 125-mm of water was applied. GPR images were produced on six transects (132 m long). GPR runs were made prior to the irrigation event and 1, 4, 7, and 25 hr after the irrigation event. GPR images show the soil surface, buried pipe, water table, and parent material (figs. 8–11); the movement of the wetting front is shown 1 hr after irrigation (fig. 9), 7 hr after irrigation (fig. 10), and 25 hr after irrigation (fig. 11). Shapes of the wetting front and uniformity curves are essentially mirror images of each other. Vellidis et al. (1989) concluded that GPR was an excellent tool for detecting wetting front movements in sandy soils and showed that wetting front determination by GPR matched water application uniformity curves remarkably well.

Several studies have determined spatial variability of geologic materials (Asmussen et al. 1986, Truman et al. 1988b, Smith et al. 1989, Vellidis et al. 1989). Asmussen et al. (1986) and Truman et al. (1988b) showed that data from GPR images can be used to create geologic material contour maps (figs. 7 and 12). These contour maps were created from GPR images and reveal actual topography of the soil surface and subsurface features (that is, geologic materials) relative to the soil surface. Accurate contour maps of geologic materials increase our understanding of drainage paths on top of geologic materials and depositional characteristics occurring above geologic materials.

Mapping Lake-Bottom Morphology

Accurate topographic survey maps and hydrologic records are needed to design reservoirs and lakes and obtain stage-storage information. Stage-storage curves provide information on available water storage, which is important in computing flood routing and downstream delivery. Hydraulic, erosion, and depositional processes alter subsurface profiles of existing lakes and reservoirs. Improved methods (instead of traditional depth-sounding methods) of determining topographic data (lake volume and bottom configuration and morphology) are needed to better understand the hydrologic processes in existing lakes and to use in water resource planning and evaluation.

Truman et al. (1991) evaluated GPR as a tool for mapping reservoir and lake bottoms and providing stage-storage information. GPR was mounted in a boat, and a 120-MHz antenna (with a scanning time of 200 nanoseconds) was towed behind the boat in a plywood box. The 1.4-ha (3.5-acre) lake was located near Plains, GA, and had 31 transects (tag-lines parallel to the lake's

dam) laid out 6.1 m apart across it. A continuous GPR image of the lake bottom was produced, revealing irregularities in water depth and lake-bottom morphology (fig. 13). In figure 13, variation in the lake bottom for the transect used for calibration and the old stream channel network can be seen. Tic-marks represent points where actual water depths were measured. The relationship between measured water depth and GPR-determined depth for the calibration transect was linear (fig. 14). A high correlation between measured and predicted water depths was due to abrupt changes in K_a between the water and the lake bottom.

From GPR data, Truman et al. (1991) created a contour map of the lake bottom (fig. 15); stage-storage data was computed at 0.305-m (1-ft) intervals. A contour map of the lake bottom allows for the study of contour elevation-water surface area and water volume relationships. Truman et al. (1991) concluded that GPR technology can define reservoir and lake storage conditions rapidly and in greater detail than conventional hydrographic survey procedures and that GPR technology is useful for evaluating changes in reservoir and lake sediment and flood storage relationships.

Mapping Hard Pans

Hard pans created by field traffic, tillage implements, and compaction contribute to poor rooting systems that can reduce crop yields. The most widely used instrument for locating hard pans is the cone penetrometer. Although this device is simple to use, obtaining valid data with it can be difficult.

Because of problems associated with the penetrometer and the need for another method to nondestructively and accurately determine depth to hard pans, Raper et al. (1990) used GPR to locate hard pans created on a Norfolk sandy loam and Decatur clay loam under lab conditions. Hard pans were created in soil bins at two depths (25 and 40 cm) and two densities (one pass and two passes with a rigid wheel). Pipes were buried parallel to the length of the bin and on top of the hard pan for depth calibration. A 500-MHz antenna had to be suspended about 25 cm above the soil surface to successfully locate the pipe and hard pan closest to the soil surface (when the antenna was placed on the ground surface, the surface reflection and first interface masked each other). GPR was used to detect and scan the hard pans, tiller pan, and soil bin wall (fig. 16). Different depths and gray scales of the two hard pans across the bin can be seen. The shallow pan on the right side of figure 16 was created with one pass of the compacting device, whereas the deeper pan on the left was created with two passes. After GPR runs were completed, penetrometer readings were taken to determine whether the hard pan was formed at a consistent depth and to compare with GPR data. Relationship between penetrometer and GPR data was linear and positive (table 2, fig. 17). Raper et al. (1990) concluded that GPR was an effective tool for determining depth to hard pans for Norfolk sandy loam and Decatur clay loam under lab conditions.

Table 2. Hard-pan depths determined by GPR and penetrometer

			Hard-pan depths (cm)†	
Soil	Depth*	n	Penetrometer	GPR
Decatur	S	48	28.3(3.0)	23.8(2.0)
Decatur	D	48	39.4(3.9)	33.2(5.9)
Norfolk	S	48	28.7(1.9)	29.4(1.8)
Norfolk	D	48	38.3(4.0)	38.2(1.9)

**S*, Shallow hard pan. *D*, deep hard pan.
†Standard deviations in parentheses.

Source: Raper et al. (1990).

Factors Affecting GPR's Performance

GPR does not work well on all soils (Hubbard et al. 1990). GPR works well on soils in the Coastal Plain region of Georgia because they are generally sandy materials overlying more clayey material. This combination commonly occurs in highly weathered soils and produces soil layers and features having abrupt changes in K_a. GPR works well on soils that have abrupt changes in K_a. However, factors have been identified that influence GPR's performance. They include position or closeness of soil horizons or features, ironstone nodules, high water contents throughout the soil profile, and water tables in fine-textured (clay) soil materials.

Interfaces or horizons that are too close together create a masking effect, that is, they appear on a GPR image as a single interface. For example, Truman et al. (1988a) found that soils with argillic horizons close to the soil surface, such as a Dothan series soil, often have the argillic horizon masked out (appears as one image with the soil surface interface). Similar problems occurred on a severely eroded Cecil soil. The same masking effect occurred in studies by Smith et al. (1989) and Vellidis et al. (1989) when monitoring water table fluctuations and water front (or wetting front) movement with GPR near geologic materials. As the water table fluctuated near the geologic material and as the water front approached geologic materials, the two interfaces masked each other out and appeared as one interface.

Truman et al. (1988a) found that argillic horizons of some soils in the Coastal Plain of Georgia are difficult to detect because of the presence of ironstone concretions. A Tifton soil had an ironstone percentage of 4.8 in the surface horizon and 32.4 in the upper part of the argillic horizon. Concretions disrupt GPR impulses and do not allow them to penetrate to lower depths.

GPR may be used to detect water tables because water tables have abrupt changes in K_a, but GPR does not perform well under near-saturated conditions throughout a soil profile. Truman et al. (1988a) found that high water contents throughout a Pelham and Clarendon series distorted GPR impulses and created an unclear GPR image. Pelham and Clarendon soils have "aquic" moisture regimes. Asmussen et al. (1986) showed the effect of water content throughout the soil profile following a period of rain (5 cm in a 4-day period) and a drought condition (0.3 cm in a 16-day period) (fig. 18).

Most water tables scanned by GPR in the Coastal Plain region of Georgia have been in coarse-textured soils. Difficulties can arise when detecting water tables (perched) with GPR in finer textured soils because these soils generally have a capillary fringe rather than a discrete interface.

Current Applications of GPR at SEWRL

Researchers at SEWRL are identifying and describing mechanisms and processes controlling water and agrichemical movement in Coastal Plain soils. Water and agrichemical movement in these sandy soils requires an understanding of subsurface conditions that control subsurface water movement and groundwater recharge. Quality of shallow or perched and deep groundwaters is a major concern at SEWRL, and loss of agrichemicals from root and vadose zones is potentially greatest from soils of this region. Coastal Plain soils are dominated by sandy surfaces (with high infiltration rates and conductivities) and have subsurface features capable of concentrating water and agrichemicals causing potential groundwater contamination. Considerable nondestructive investigations are occurring at SEWRL to evaluate spatial variability of subsurface features that cause lateral and preferential flow. GPR has been proven useful in detecting and determining the spatial variability of subsurface features in Coastal Plain soils in a continuous, nondestructive manner.

A study at SEWRL is being conducted to evaluate processes controlling agrichemical transport in the Claiborne aquifer recharge area in the Coastal Plain region of Georgia. Objectives of the study are to determine transport rates and pathways of agrichemicals in the root zone and vadose zone and into groundwater and to relate these findings to soils, geology, climate, and agricultural practices. GPR has an important role in initial site investigation in that it is being used as a nondestructive method for identifying subsurface features that alter water and agrichemical flow paths and for defining sampling locations that can be instrumented and used to evaluate preferential transport of water and agrichemicals.

A 1-ha field plot consisting of Troup and Eustis sand is being characterized in terms of surface and subsurface morphology prior to first application of any tracers or agrichemicals. Soil properties (organic carbon, pH, texture, saturated and unsaturated hydraulic conductivity, and bulk density) and ground-truth data will be determined from sampling border areas established around the plot. GPR (120-MHz antenna at 200 nanoseconds) has been used on a 10- by 10-m grid to extend these properties and depth to dominate subsurface features into the plot. GPR data are being used to identify preferential pathways and sampling locations.

GPR is useful for detecting and determining the lateral extent of subsurface features capable of altering water and agrichemical movement (fig. 19). The clay layer in figure 19 is shown on a calibration transect that slopes to the north at about 10 percent (soil surface has a slope

of about 1 percent). The clay layer is 5- to 15-cm thick and is located in about a 15-m^2 area. From GPR imagery and ground-truth data, a contour map of this clay layer was created (fig. 20). Such a map allows potential preferential flow paths to be identified and potential sampling locations to be determined.

Conclusions

This publication summarizes the past and current GPR studies at SEWRL. The following conclusions can be made:

1. GPR may be used to monitor surfaces of subsurface horizons or features that have contrasting K_a values.

2. Depth and lateral extent of subsurface features (argillic horizons, water tables, water front movement, hard pans, geologic materials, etc.) can be accurately measured by GPR.

3. GPR is useful for mapping lakes, detecting lake-bottom variations, locating old stream channels, and accurately determining water depths.

4. Factors affecting GPR's performance include position or closeness of soil horizons or features, ironstone nodules in a near-surface horizon, high water contents throughout a soil profile, and water tables in fine-textured soils (causing a capillary fringe).

5. Advantages of GPR systems are that they speed up site investigations, they provide continuous resolutions of selected subsurface features being investigated, and they are nondestructive to soil.

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Figures

Figure 1.
Radar images of a Fuquay sand. *A*, Surface of the soil. *B*, Top of the argillic horizon. *C*, Embedded pipe.

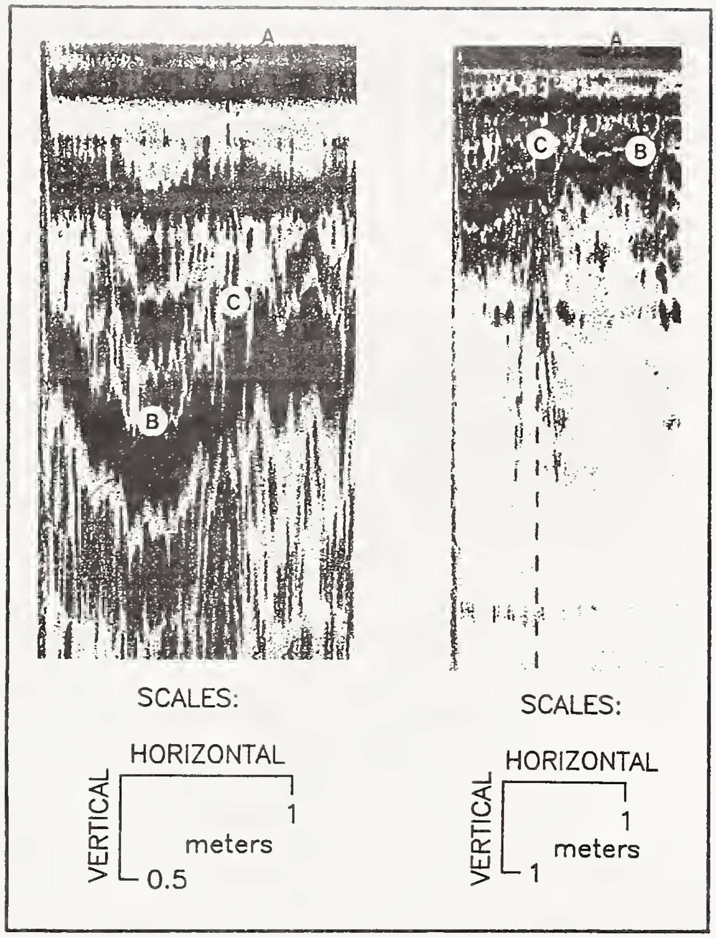


Figure 2.
Relationship between measured depth to the argillic horizon versus depth determined by GPR (data from Asmussen et al. 1986 and Truman et al. 1988b)

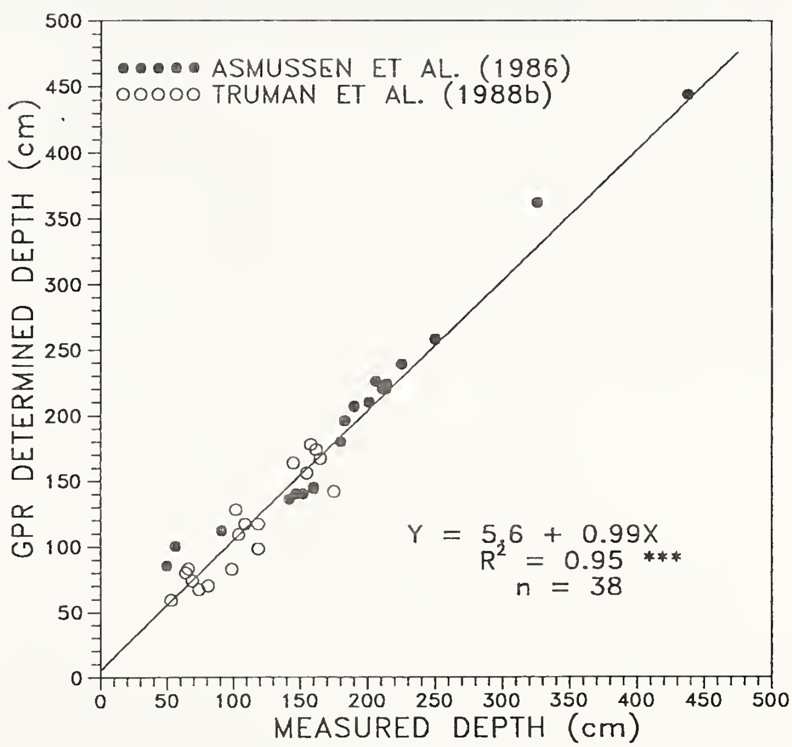


Figure 3.
GPR image showing spatial variability in a Fuquay sand (from Truman et al. 1988b). *A*, Argillic horizon depth.

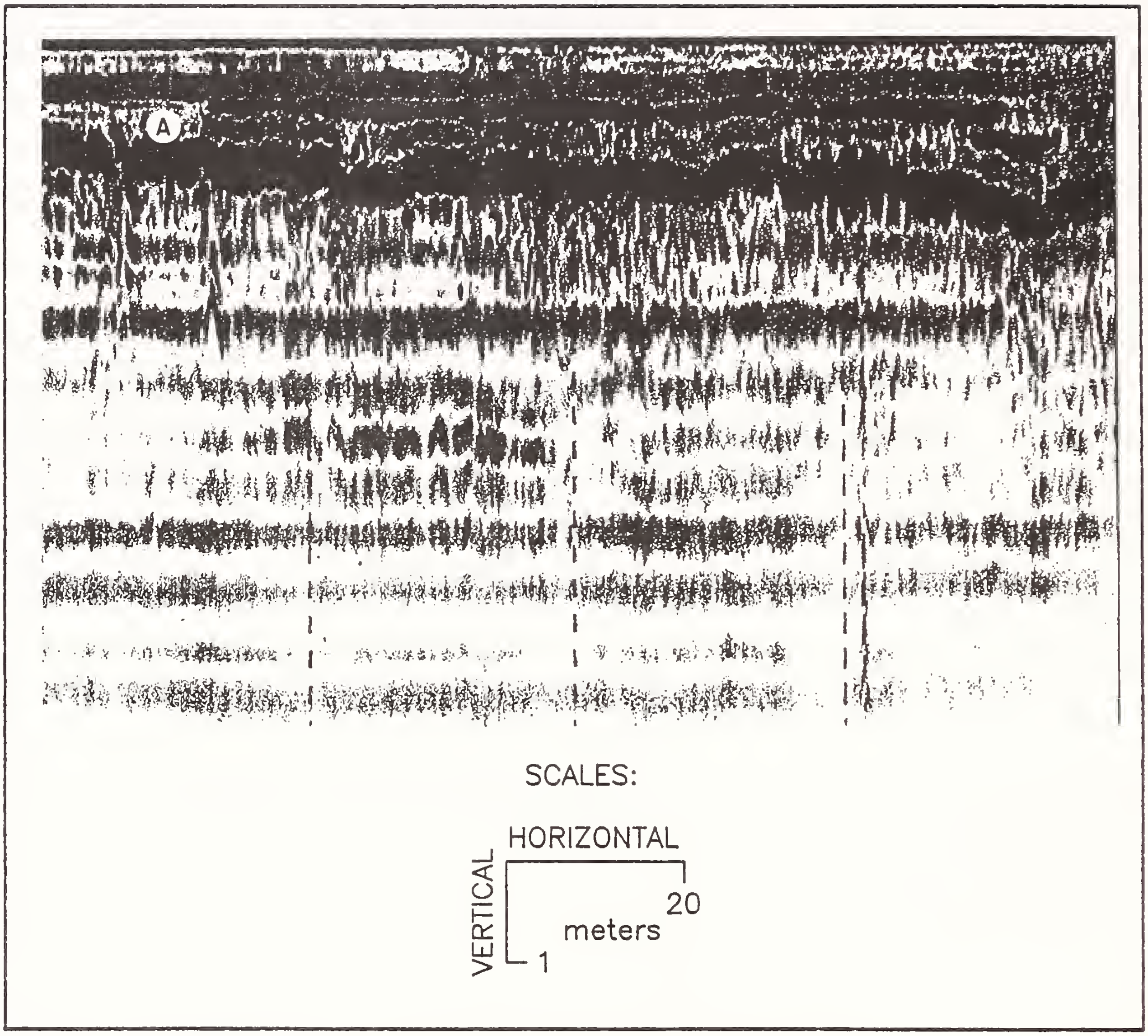


Figure 4.

Depth to the argillic horizon determined by GPR and ground-truth data (from Asmussen et al. 1986)

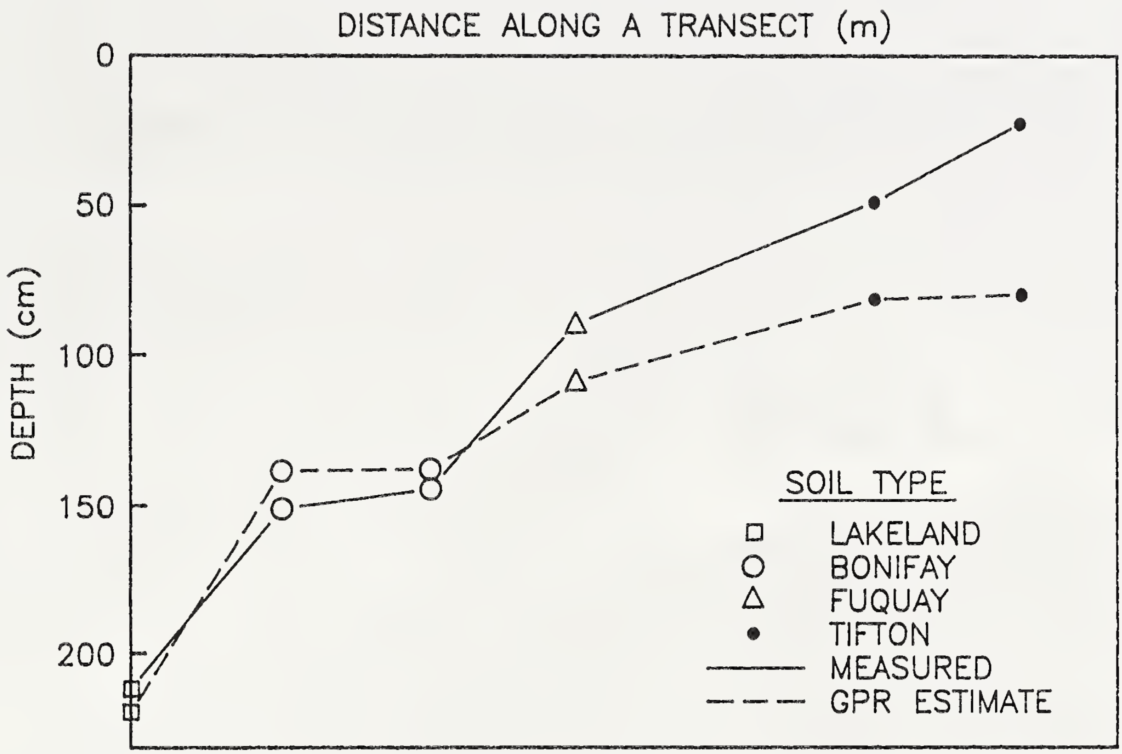


Figure 5.
GPR image showing spatial variability in a Kershaw sand (from Truman et al. 1988b). *A*, Water table depth. *B*, Geologic material depth.

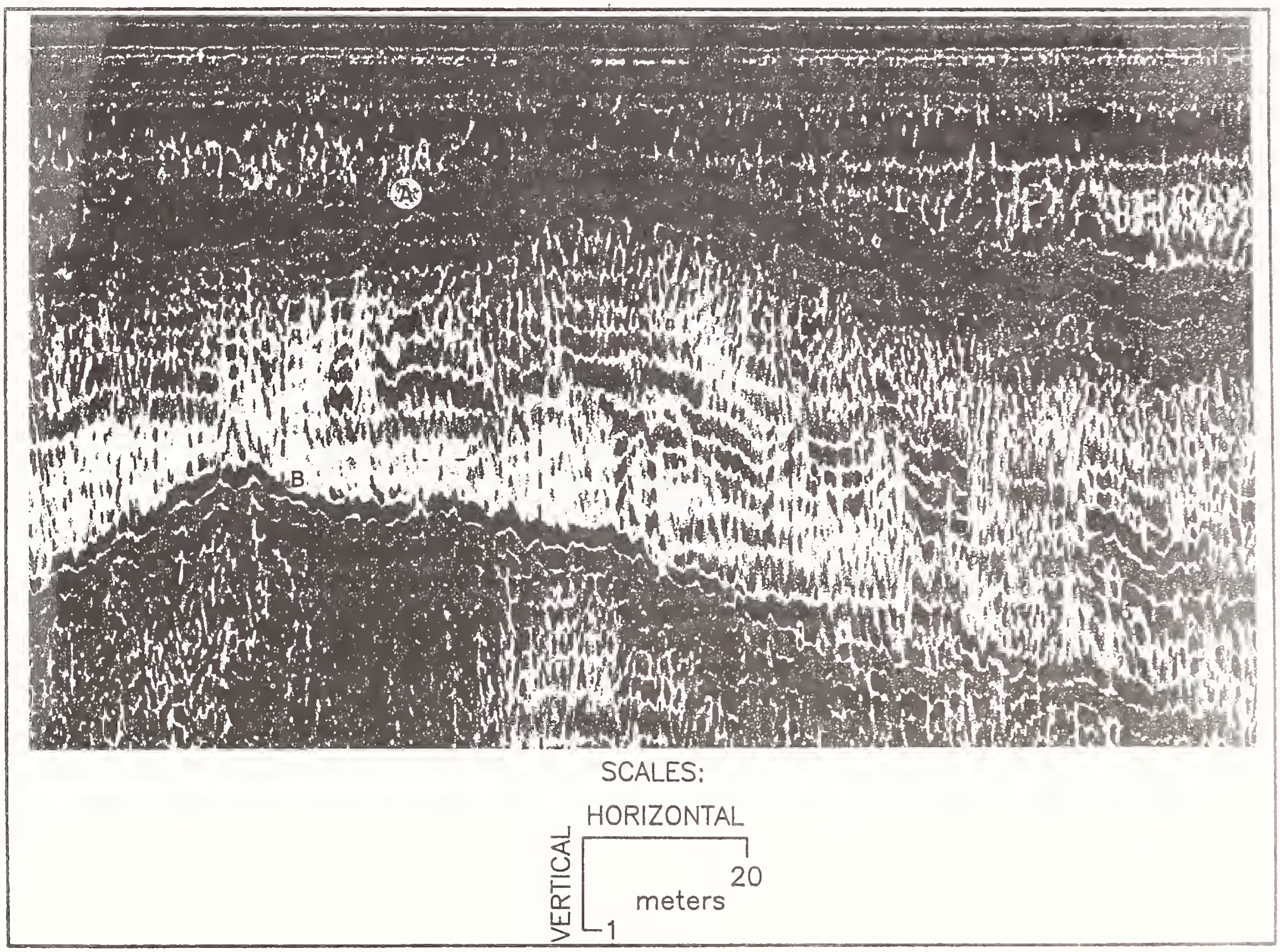
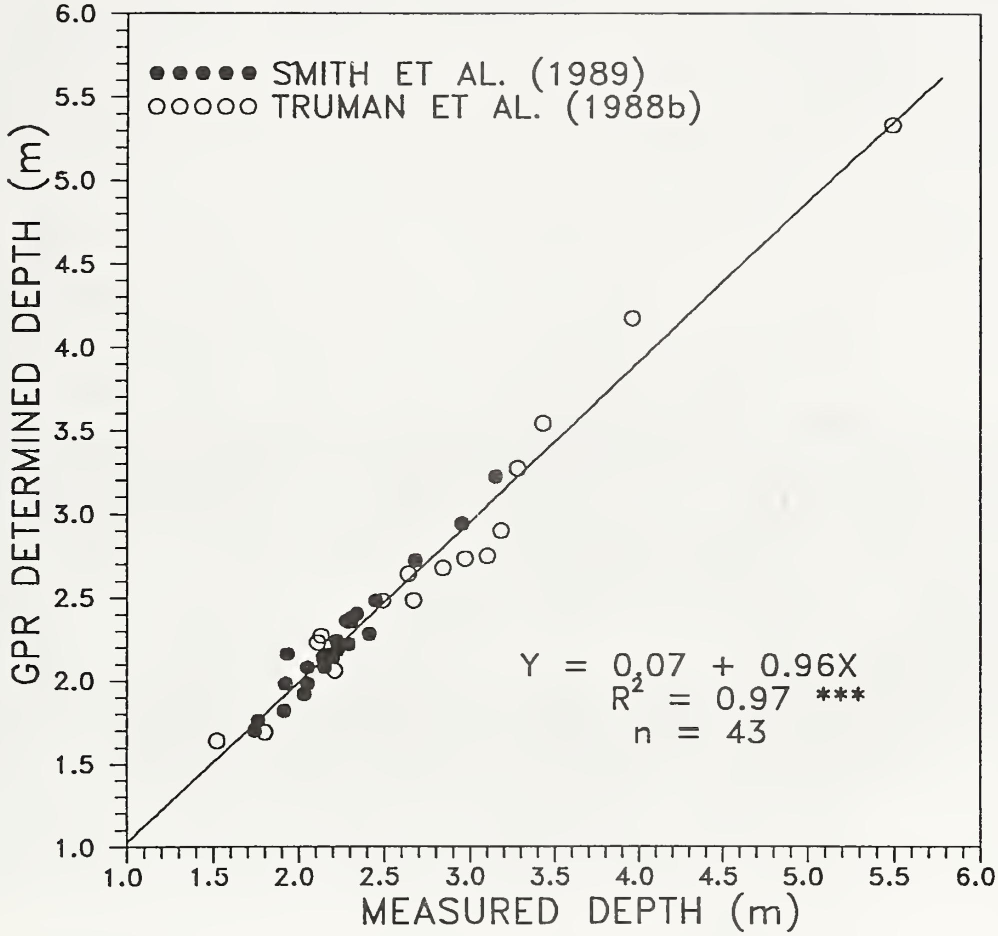


Figure 6.
Relationship between measured depth to the water table versus depth determined by GPR



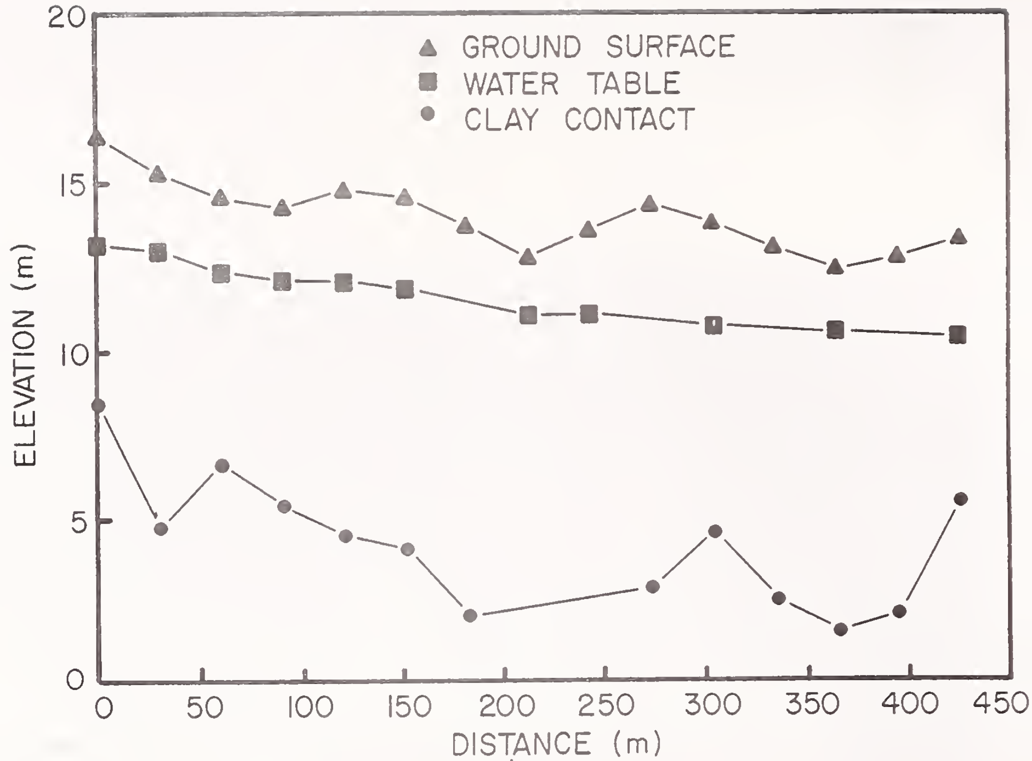


Figure 7.
Transect three of the Kershaw sand showing surface elevation, water table, and clay contact (geologic material). Water table and clay contact data were obtained from a GPR image (from Truman et al. 1988b).

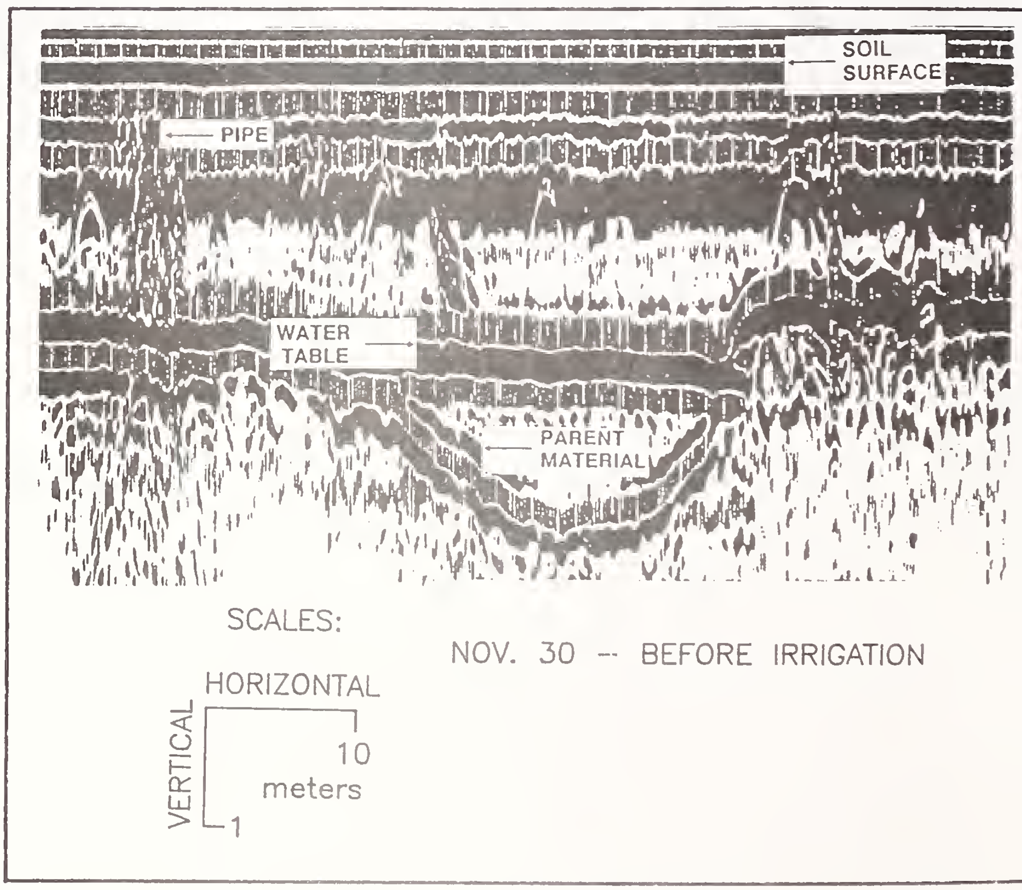


Figure 8.
GPR image showing the soil surface, buried pipe, water table, and parent material (geologic material) before a 125-mm irrigation event (from Vellidis et al. 1989)

Figure 9.
GPR image showing the soil surface, buried pipe, water table, parent material (geologic material), and wetting front 1 hr after a 125-mm irrigation event (from Vellidis et al. 1989)

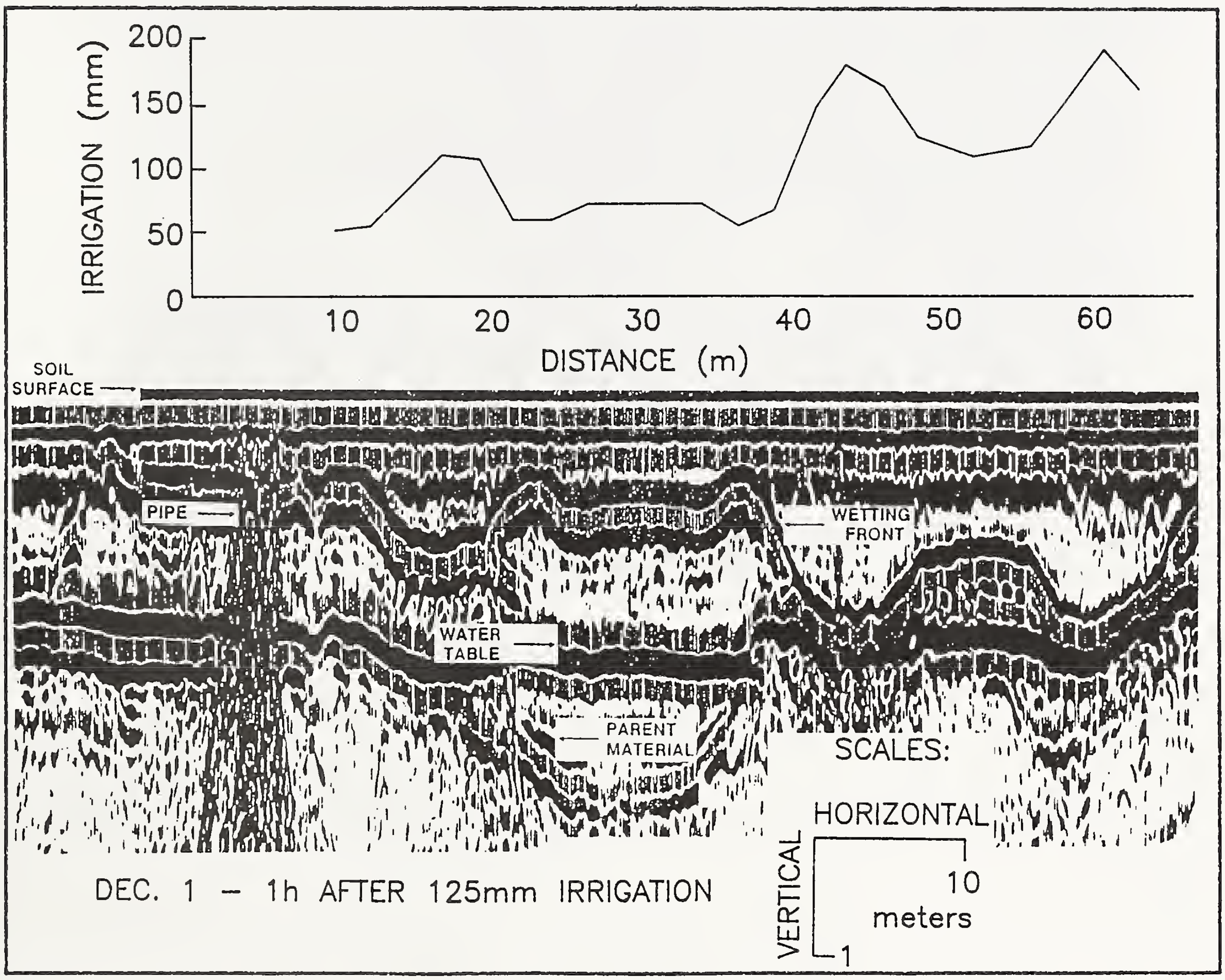


Figure 10.
GPR image showing the soil surface, buried pipe, water table, parent material (geologic material), and wetting front 7 hr after a 125-mm irrigation event (from Vellidis et al. 1989)

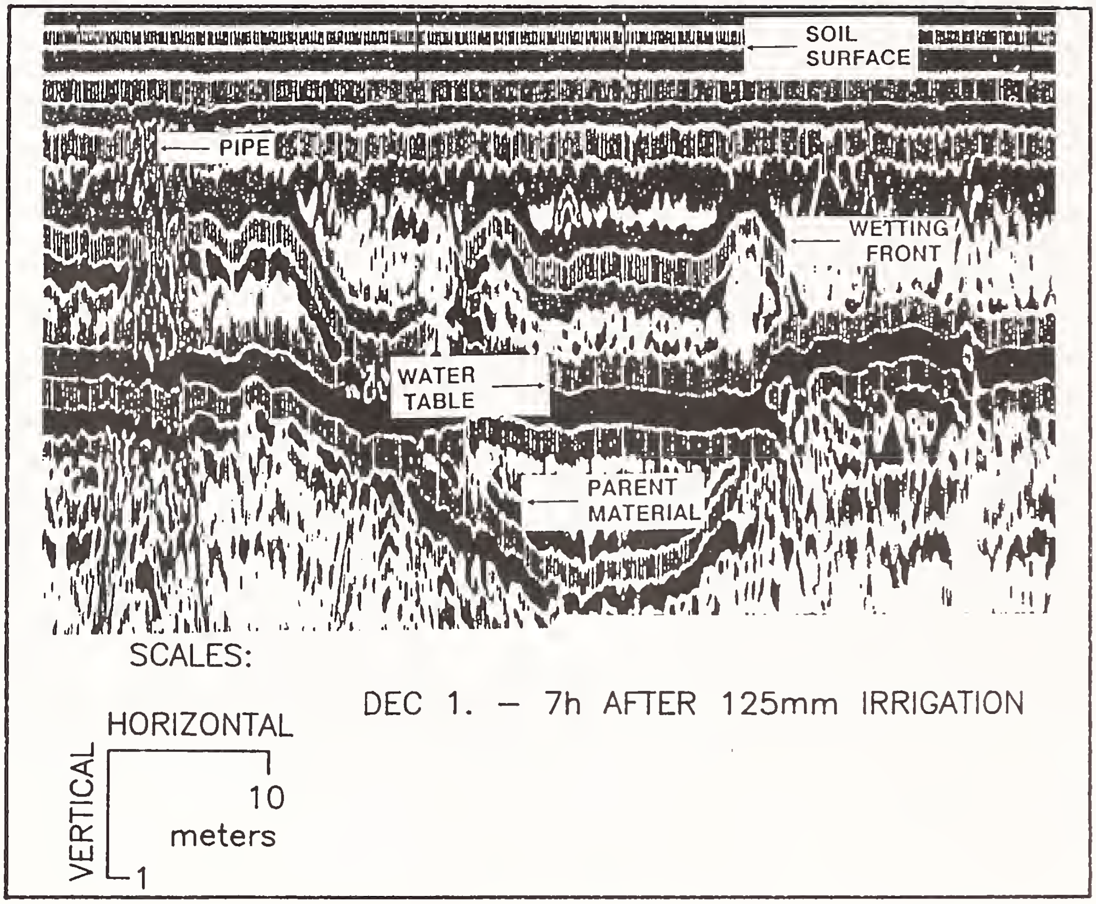


Figure 11.
GPR image showing the soil surface, buried pipe, water table, parent material (geologic material), and wetting front 25 hr after a 125-mm irrigation event (from Vellidis et al. 1989)

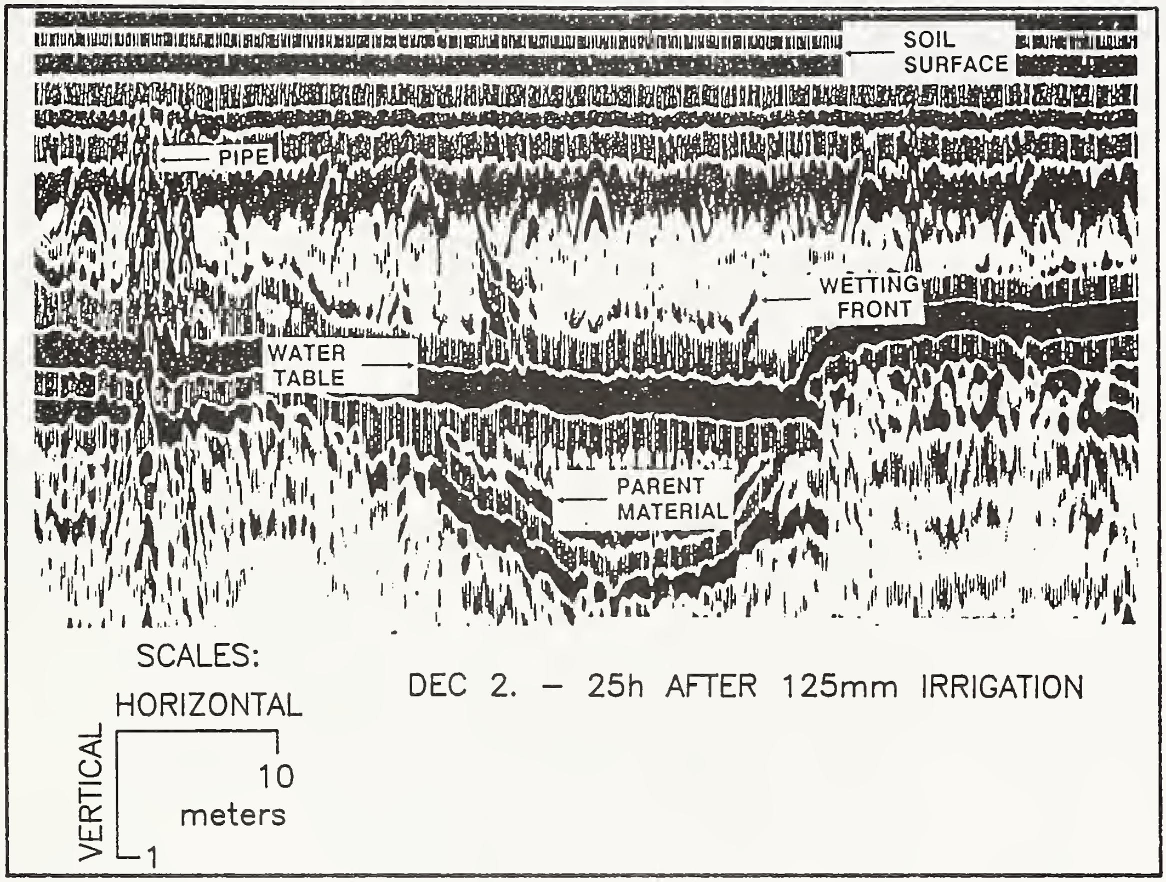
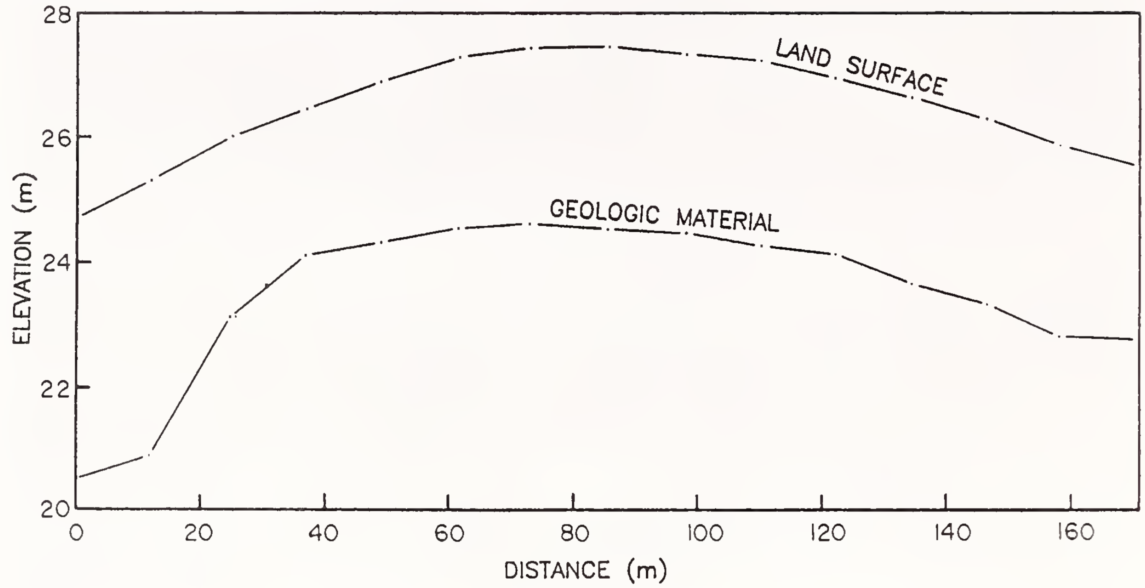


Figure 12.
Profile of soil surface and geologic material created from GPR data (from Asmussen et al. 1986)



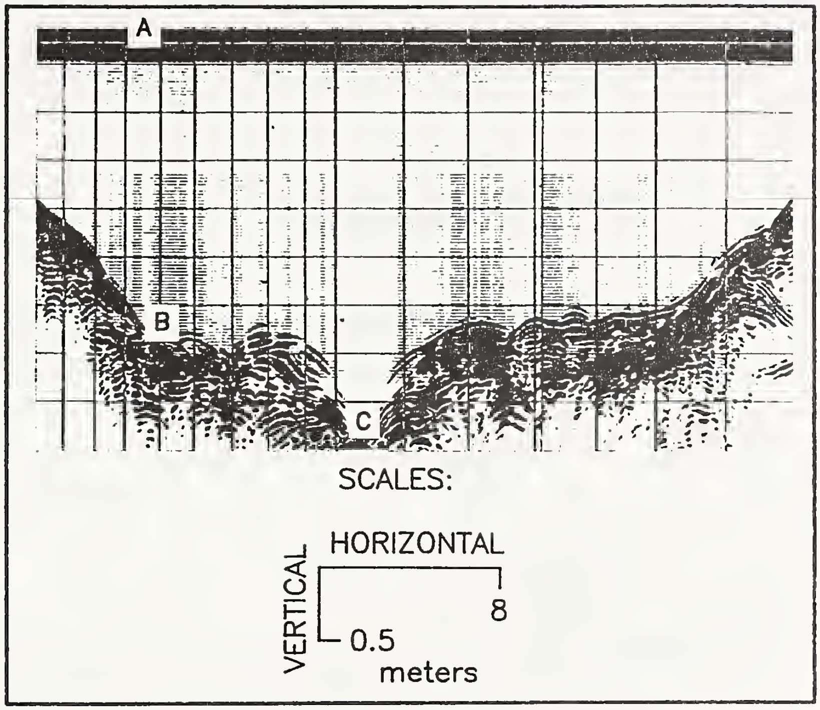


Figure 13.
Radar image of the lake-bottom calibration transect (from Truman et al. 1991). *A*, Water surface. *B*, Lake bottom. *C*, Old stream channel network.

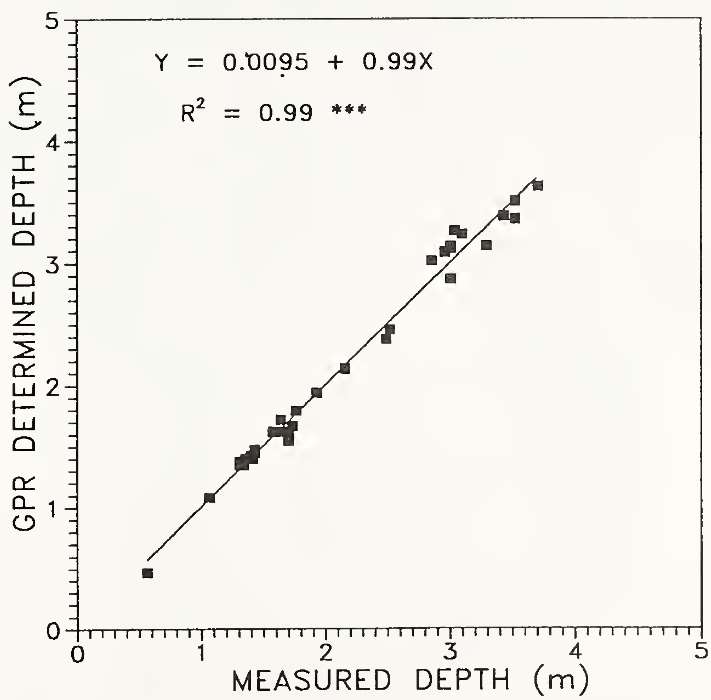


Figure 14.
Relationship between actual (measured) depth of water and water depth determined by GPR (from Truman et al. 1990)

Figure 15.
Contour map of lake bottom created from GPR data (from Truman et al. 1991)

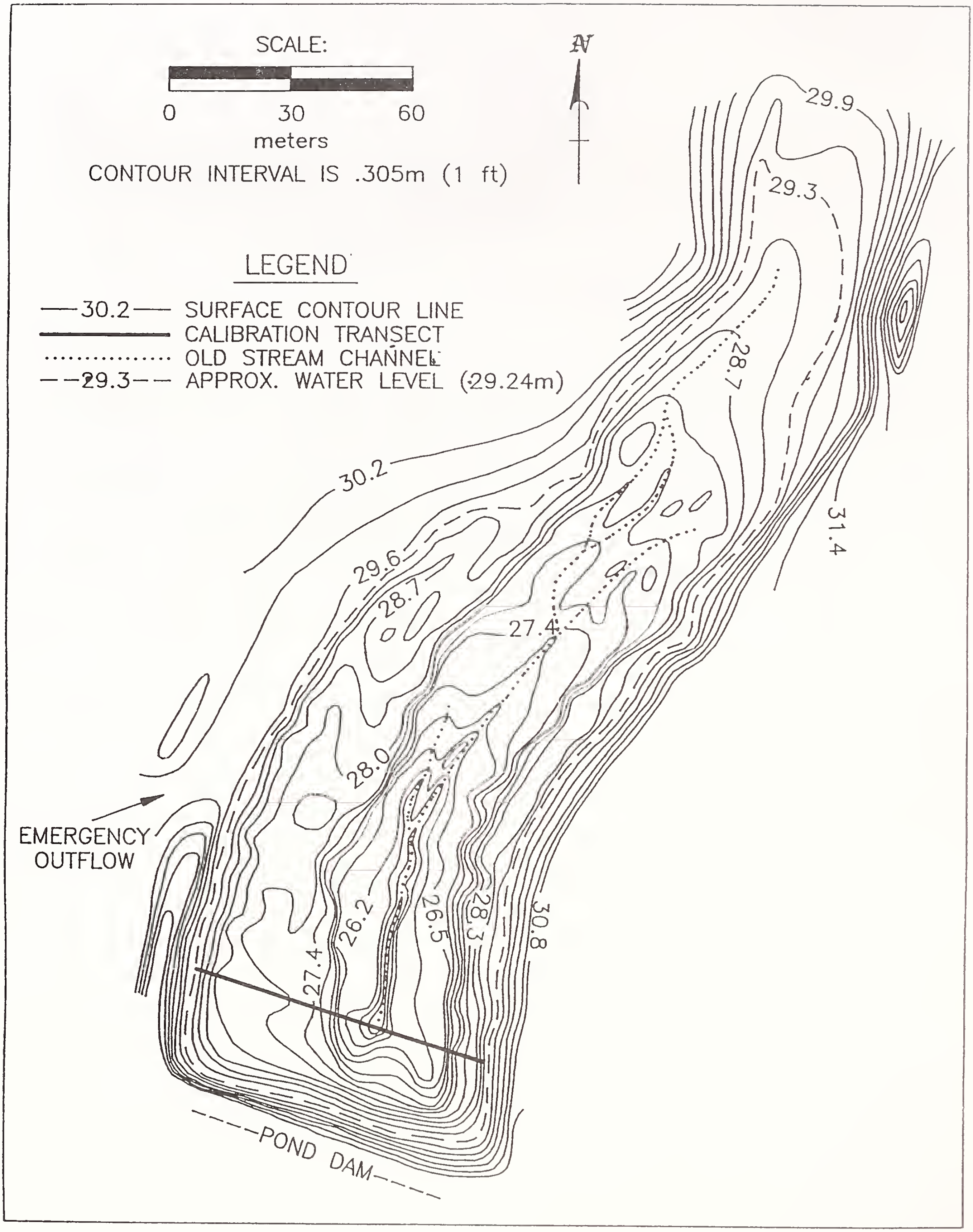


Figure 16.
GPR image of hard pans, tiller pan, and soil bin wall reflections in a Norfolk sandy loam (from Raper et al. 1990)

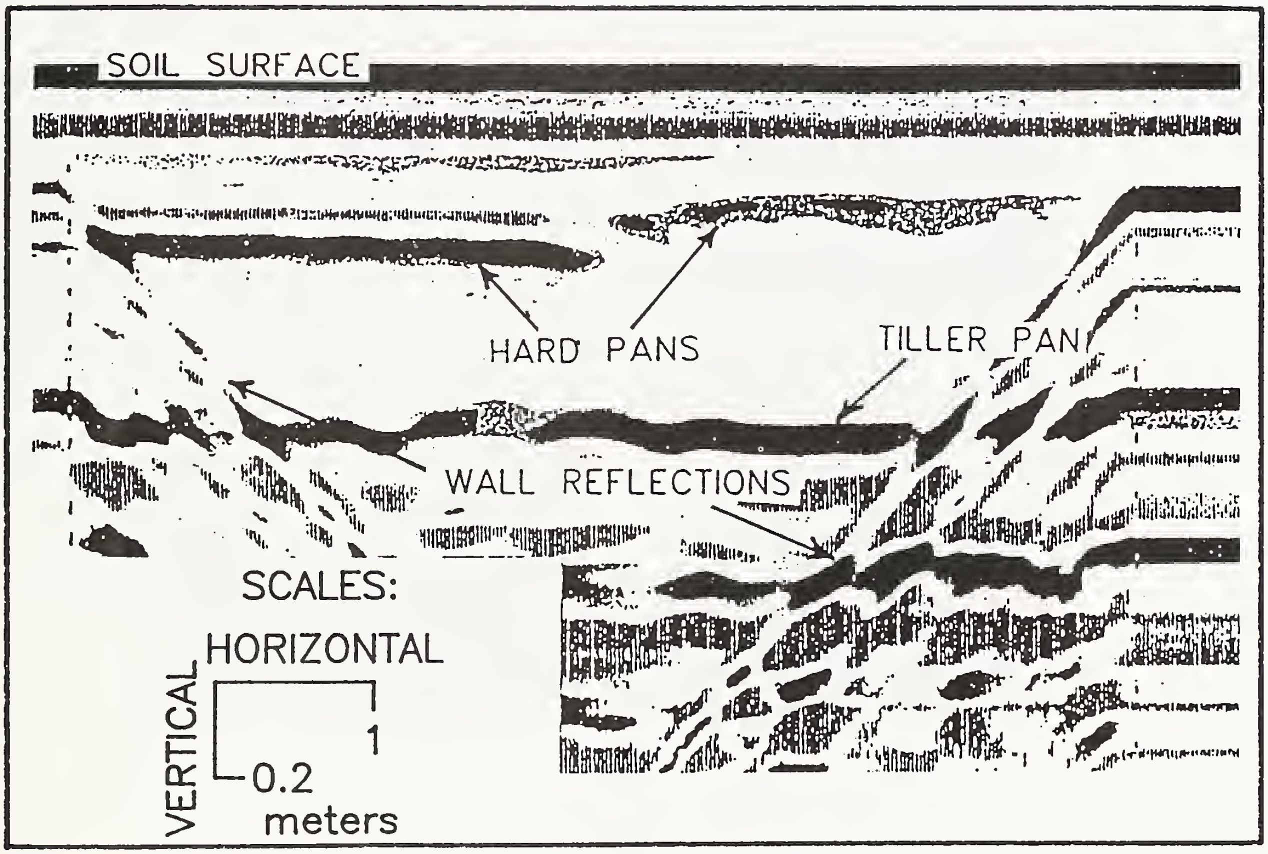


Figure 17.
Hard-pan depth determined by a penetrometer versus that determined by GPR (from Raper et al. 1990).
A, From a Norfolk sandy loam. *B*, From a Decatur clay loam.

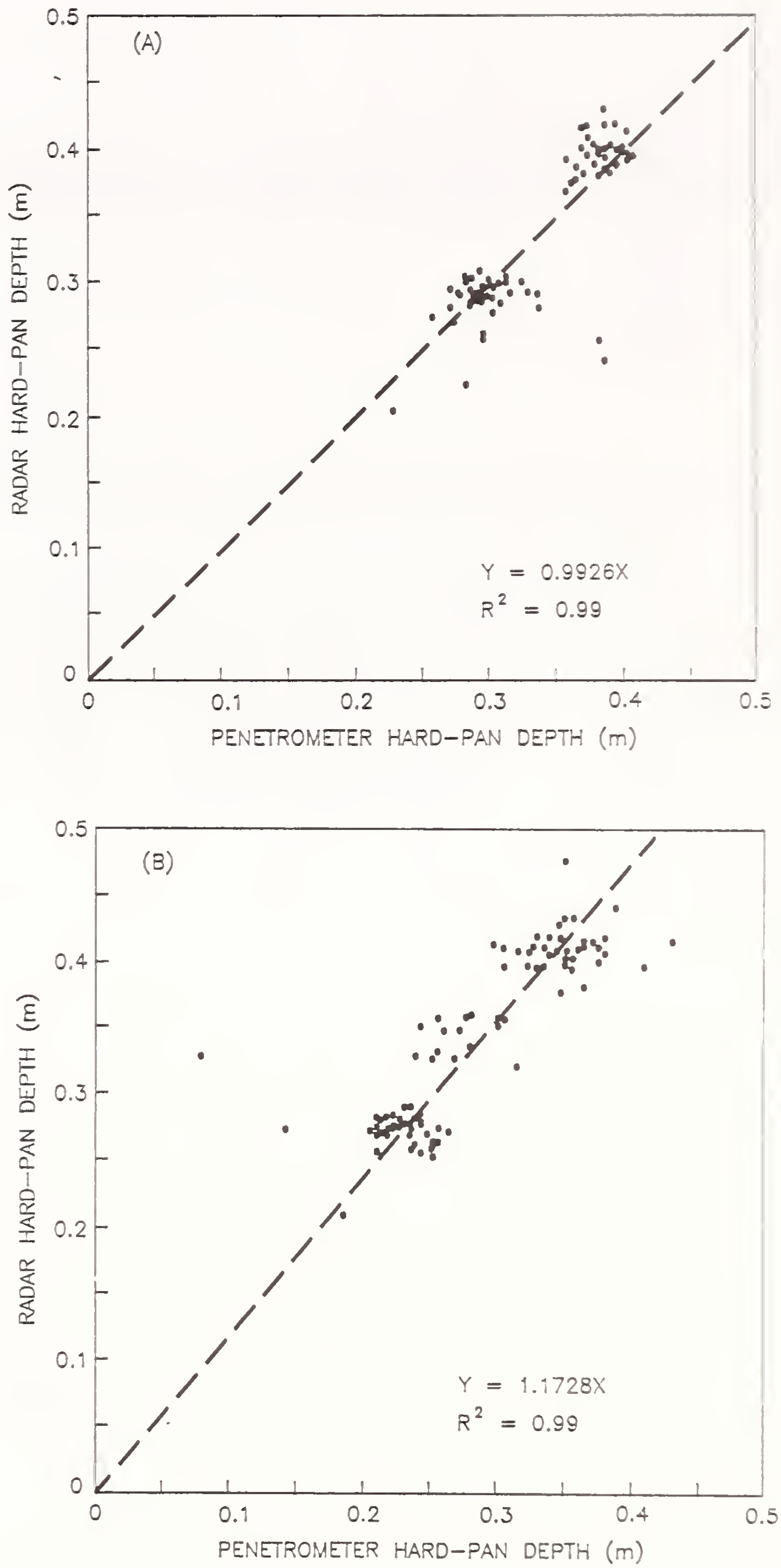


Figure 18.

Effects of water content throughout a Lakeland sand on GPR imagery (from Asmussen et al. 1986). *A*, Following a period of rainfall. *B*, Following drought.

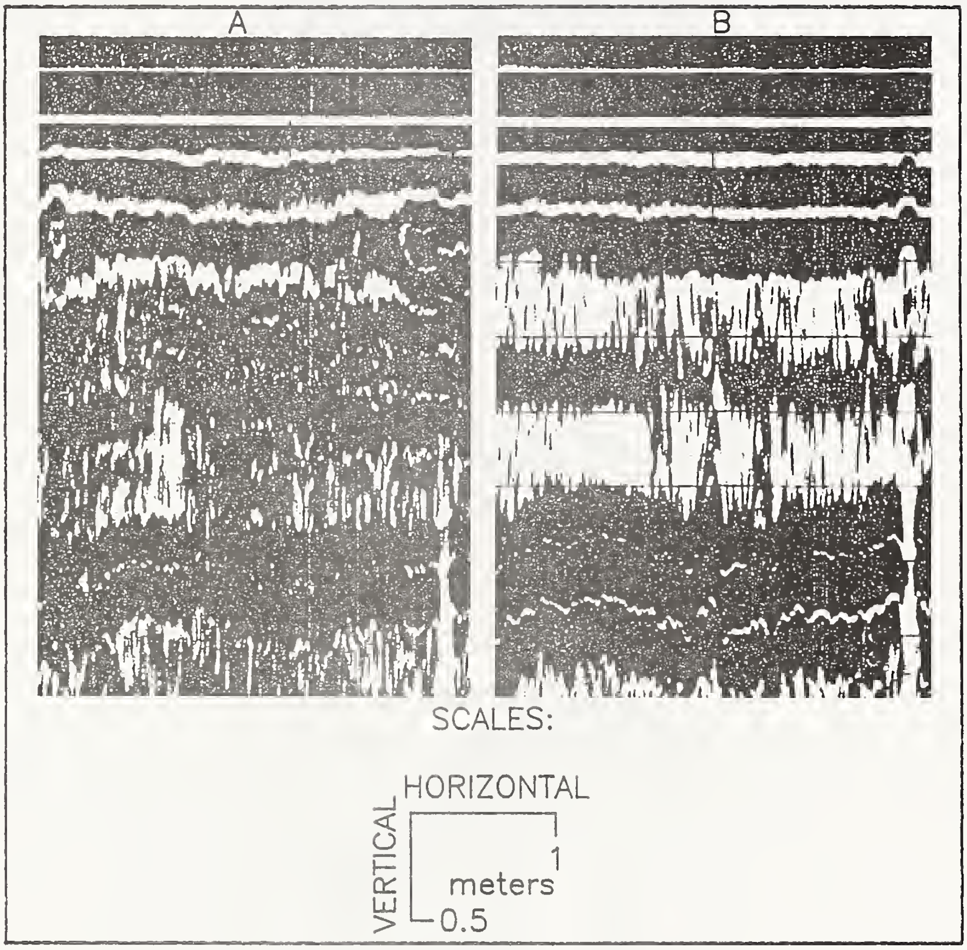


Figure 19.
GPR image of a calibration transect showing the soil surface and a sloping clay layer in a Troup sand. *A*, Top of sloping clay layer. *B*, Bottom of sloping layer.

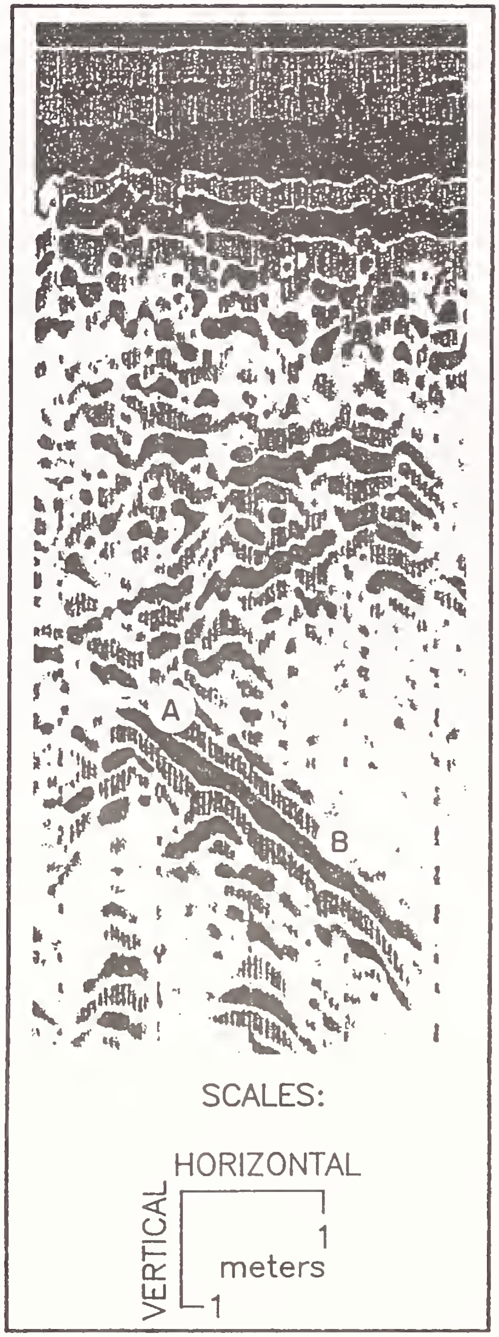


Figure 20.
Contour map created from GPR data to show the subsurface clay layer